Co-Optimization of
Fuels & Engines

HD MCCI: Impacts of fuel properties on combustion, injection characteristics and emissions controls

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June 3, 2020
Project # FT078

2020 DOE Vehicle Technologies Office
Annual Merit Review

better fuels | better vehicles | sooner

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Overview

	Task	Description	FY19	FY20	To date	End
In-Cylinder Emissions Reduction	E.1.4.1 Powell Argonne	X-ray Measurements of Injection and Mixture Formation	$155k		$155k	FY19
In-Cylinder Emissions Reduction	G.2.18 Som Argonne	Effect of Fuel Properties on In-nozzle Cavitation and Ensuing Spray Using CFD	$120k		$120k	FY19
In-Cylinder Emissions Reduction	F.2.4.1 Burton NREL	Mixing Controlled Compression Ignition Fuel Property Effects	$115k	$230k	$345k	FY20
In-Cylinder Effects on Emissions Control	E.2.2.9 Busch SNL	Impact of oxygenates on catalyst heating operation	$160k	$200k	$360k	FY21
In-Cylinder Effects on Emissions Control	E.2.2.8 Wissink ORNL	Impact of cetane number and volatility on catalyst light-off and cold-start emissions	$100k		$100k	FY19
In-Cylinder Effects on Emissions Control	E.2.1.8 Wissink ORNL	MD/HD Multimode Catalyst Light-off/Light-down		$300k	$300k	FY21
		Total	**$650k**	**$730k**	**$1.38M**	

Timeline

Tasks started in FY19 and FY20 and all are expected to conclude by or before FY21

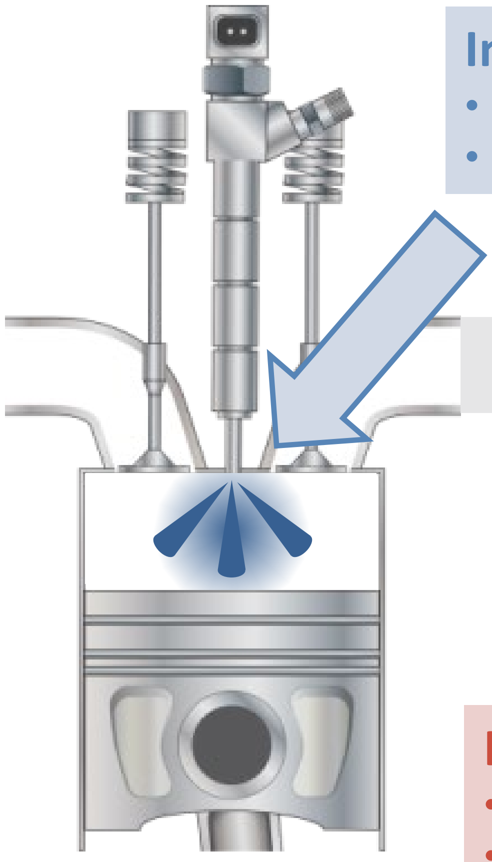
Barriers

- A comprehensive understanding of fuel sprays, combustion, and emissions formation with support from advanced diagnostics and high-fidelity modeling tools is needed to develop optimal combustion system design
- Understand and improve combustion during cold start and low load operation to reduce emissions

Partners

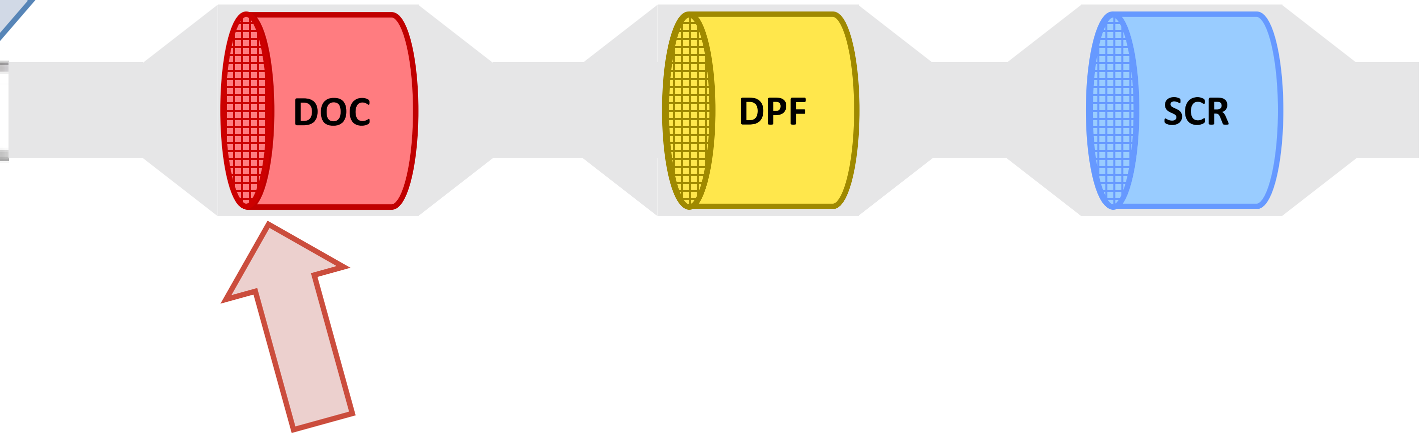
- Cavitation: Powell, Torelli, Pickett, ECN, Co-Optima Fuels Team
- MCCI fuel effects: Ford
- Cold start & light-off: Ford, Daimler, Neste, Cummins
- Oxy fuel blends and cat heating: W-ERC, Ford

Develop a fundamental understanding of the relationship between fuel properties and emissions



In-Cylinder Emissions Reduction (sprays, mixture formation, combustion)

- Cavitation and erosion alter injection and combustion, and depend on the physical properties of the fuel
- MCCI bio-derived blendstock fuel properties effects on performance and emissions



In-Cylinder Effects on Emissions Control (catalyst heating & light-off, cold start)

- Effects of CN, volatility, oxygenates on cold start and catalyst light-off
- Fuel properties impact combustion, emissions, and aftertreatment performance

Relevance

- **In-cylinder emissions reduction requires detailed knowledge of fuel effects on injection, mixture formation, and combustion**
  - **Objectives**: Perform nozzle flow measurements and simulations to characterize the influence of critical fuel properties on cavitation. Identify fuel properties that increase cavitation and erosion. Identify the effects that fuel properties have on engine performance and emissions.
  - **Impact**: Improved fundamental understanding of cavitation and erosion. Integrate a new cavitation erosion model into a computational screening tool for new fuels. Better understanding of what biomass derived blendstocks can do to improve performance and emissions for internal combustion engines.
- **Decreasing emissions at cold start and low load operation requires either decreased engine-out emissions, or faster catalyst light-off**
  - **Objectives**: Assess the impact of fuel properties such as cetane number, volatility, oxygenate and aromatic content on the ability to increase exhaust temperature, decrease HC emissions, and increase catalyst activity at low temperatures.
  - **Impact**: Improved understanding of how fuel properties can be manipulated in order to decrease emissions under cold start and low load conditions

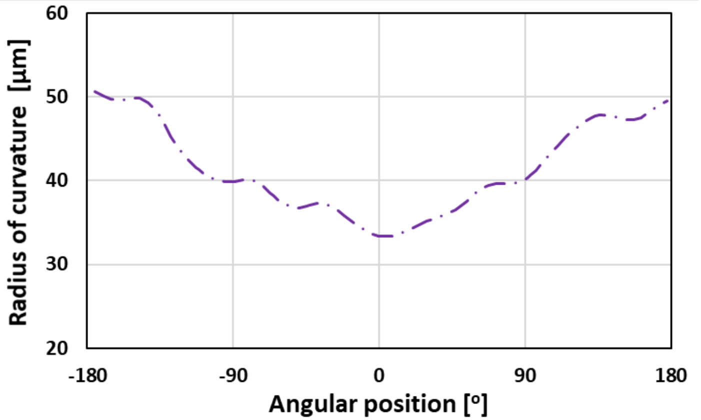
Milestones

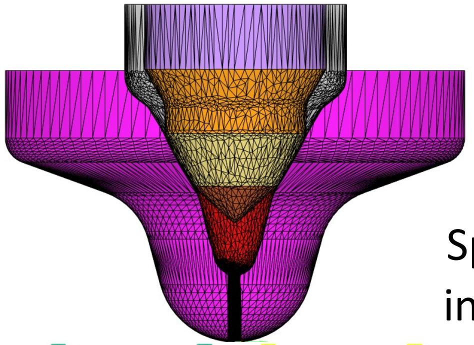
Task	Month / Year	Description of Milestone or Go/No-Go Decision	Status
E.1.4.1 Powell Argonne	June 2019	X-ray imaging of cavitation in MCCI nozzles will be completed, examining the effect of three fuel blends on the cavitation intensity and distribution in the nozzle	Complete
F.2.4.1 Burton NREL	Mar 2020	Complete engine tests with MCCI blendstocks	Delayed due to COVID-19
E.2.2.9 Busch SNL	Dec 2019	Commission medium-duty compression ignition engine and complete shakedown testing	Delayed / completed in Q2
E.2.2.9 Busch SNL	Sept 2020	Complete performance and emissions measurements with oxy blends in medium-duty diesel engine	On track
E.2.1.8 Wissink ORNL	Sept 2020	Quantify impact of fuel effects on catalyst light-off/light-down performance.	On track

Approach
In-Nozzle Flow Measurements and Modeling

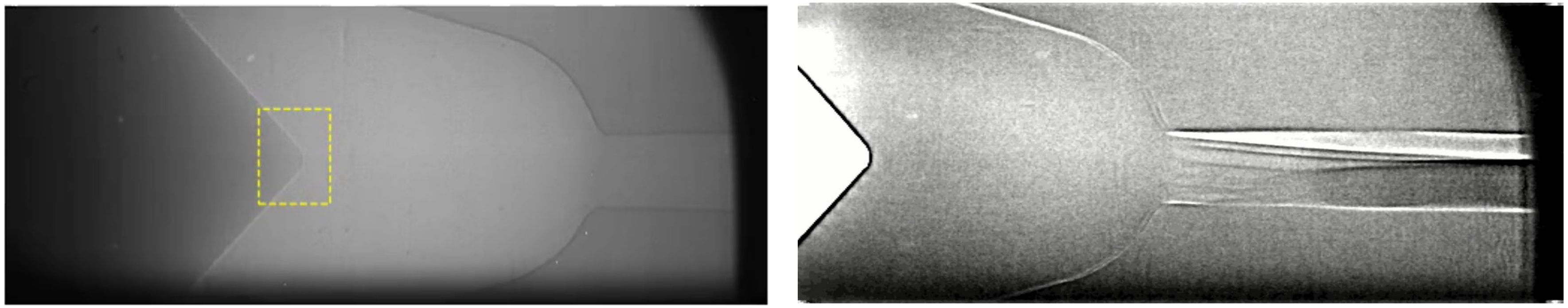
E.1.4.1: ended FY 2019
G.2.18: ended FY 2019

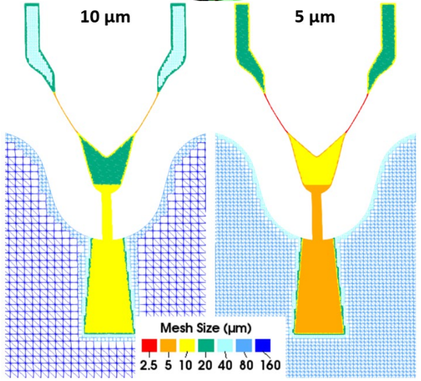
- **Fuel property effects on in-nozzle cavitation were assessed using Large Eddy CFD Simulations and leveraging X-ray experiments[1]:**
  - **Single-hole injector specifically designed to trigger cavitation studied to verify model's predictive capability**
  - **Real nozzle geometry and transient needle motion profiles used to provide accurate boundary conditions**
  - **Simulations validated against X-ray measurements of in-nozzle flow**
- **Areas of investigation**
  - **Effect of fuel properties on cavitation (n-dodecane, iso-octane)**
  - **Effect of injection pressure on internal flow characteristics (500, 1500 bar)**
  - **Definition of best practices for CFD setup and mesh size**





ECN Spray C injector

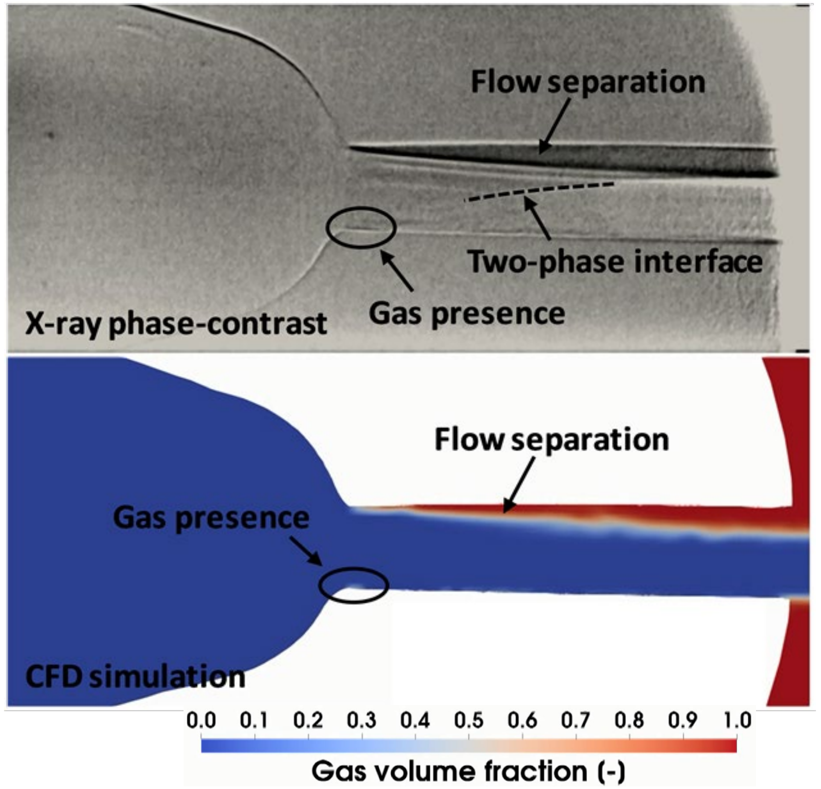




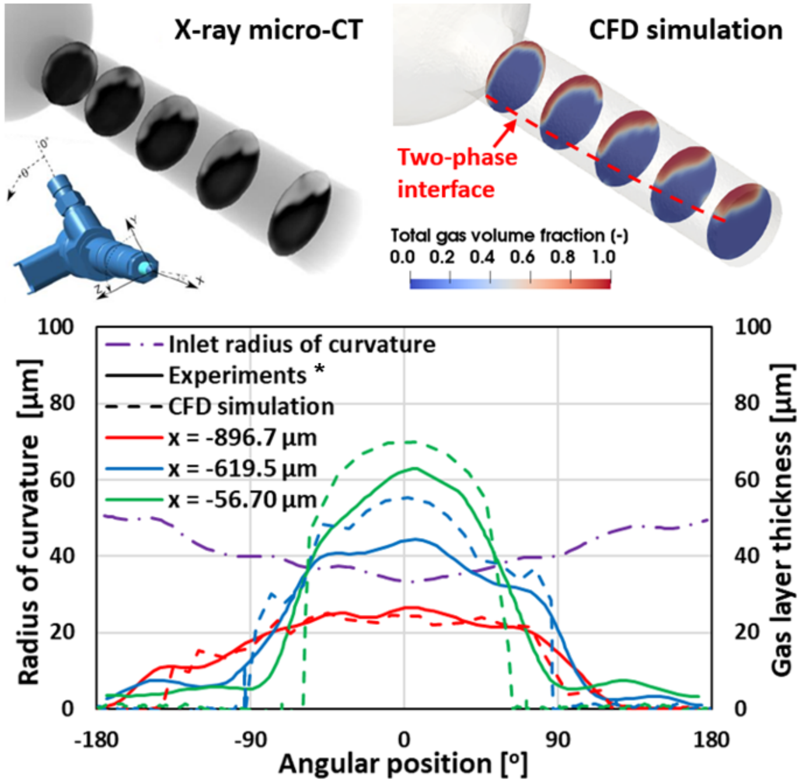
[1]Powell, C., and co-workers at Argonne

Prediction of internal flow characteristics[1,2]

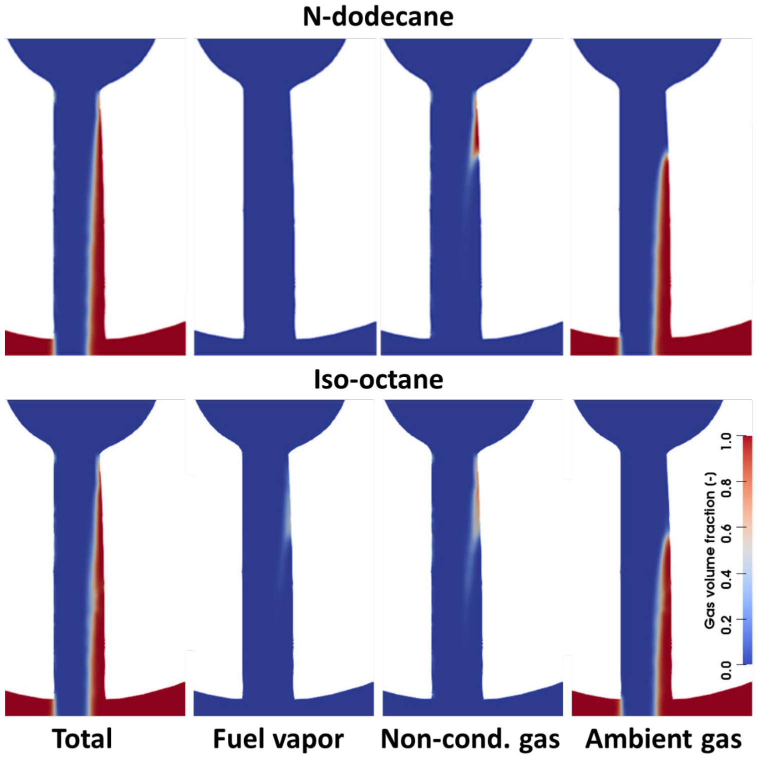
Validation of internal flow predictions using experimentally measured needle motion



Qualitative and quantitative validation of gas layer thickness



Identification of the gaseous medium composition inside the injector orifice



- Time-resolved X-ray measurements revealed the flow separation inside the nozzle
- Simulations correctly captured the 3-D distribution of the low-density fluid observed in experiments
- CFD provided insights in the composition of the gas phase highlighting the effects of fuel properties

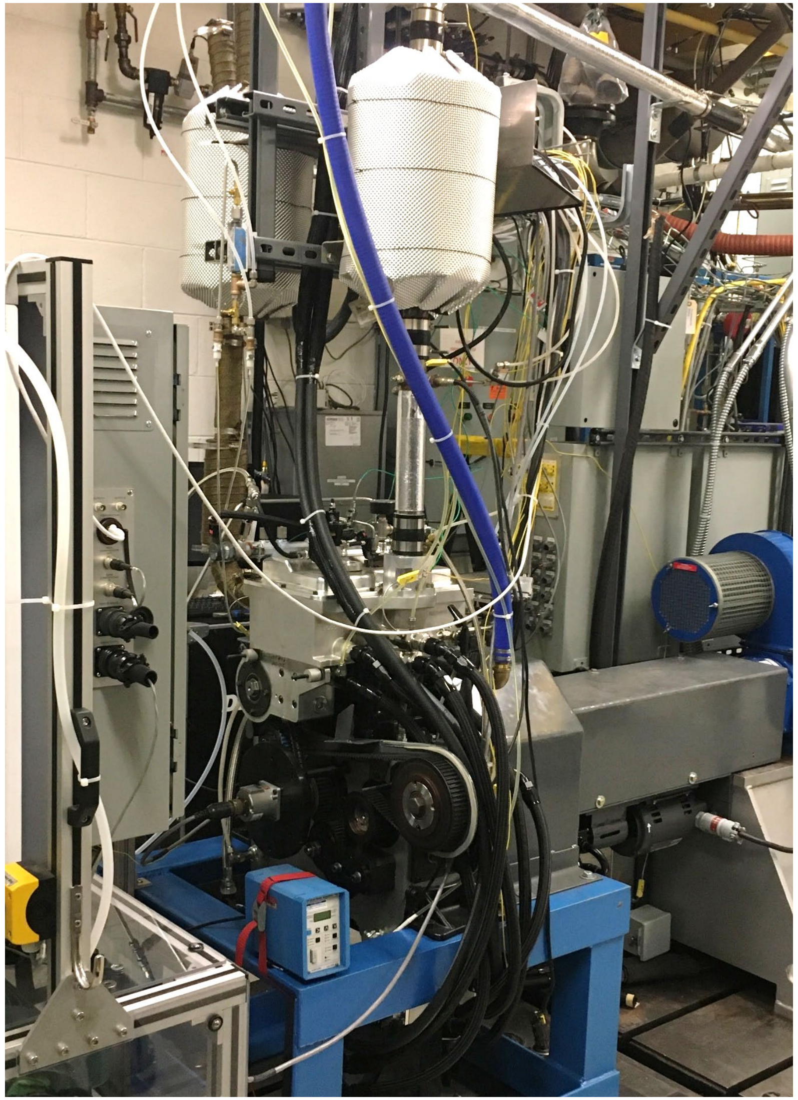
[1]Tekawade et al., ILASS-Americas 2019 [2]Guo et al., SAE 2020-01-1154

Approach
Mixing Controlled Compression Ignition Fuel Property Effects (Burton)

F.2.4.1: ending FY 2020

- **NREL's new medium-duty single cylinder research engine has been fully commissioned and is now operational.**
  - Based on the 6.7L Power Stroke®: Stock piston/connecting rod, fuel injector, valves, intake/exhaust port geometry. (Collaboration with Ford)
  - Engine Capabilities: Fully independent ECM, independent high-pressure fuel cart, EGR, intake heating, exhaust back-pressure control.
  - Emissions Equipment: Horiba MEXA-One with EGR for gases, AVL Micro Soot Sensor for PM.
- **Biomass-derived fuel blendstocks to be studied (based on selections from previous study[1]): ULSD Cert as baseline fuel and the base for 30% blends with the following (biodiesel, renewable diesel HD, 1-decanol, hexyl hexanoate, dibutoxy methane, isoamyl ether)**
- **EGR and SOI sweeps performed for the following engine operating conditions:**

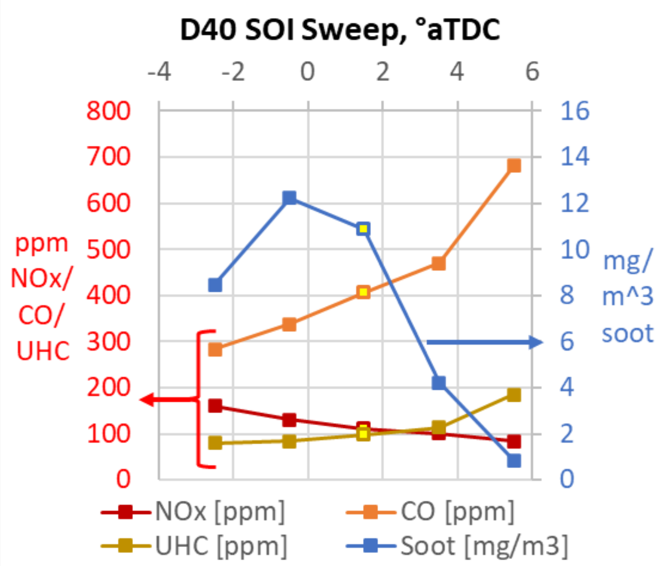
Condition	Speed [rpm]	gIMEP [bar]
A20	600	4
D40	1300	8
G60	2075	12

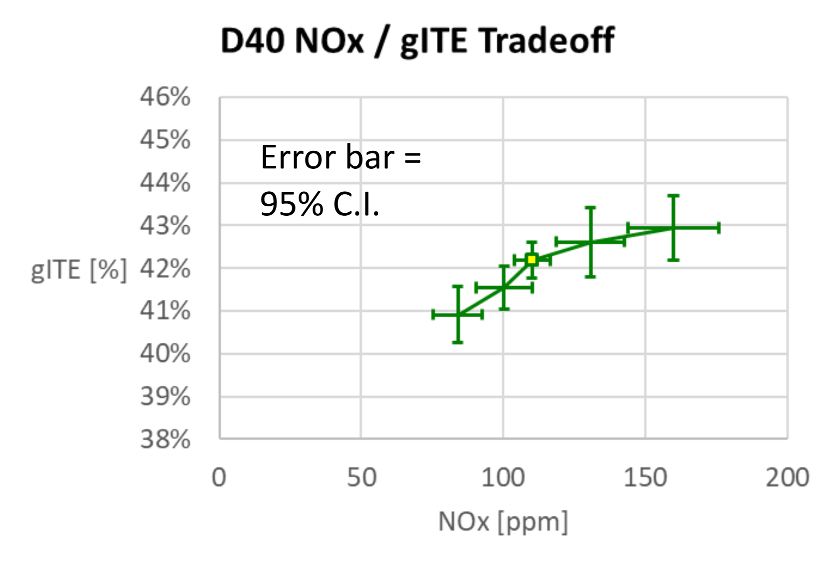


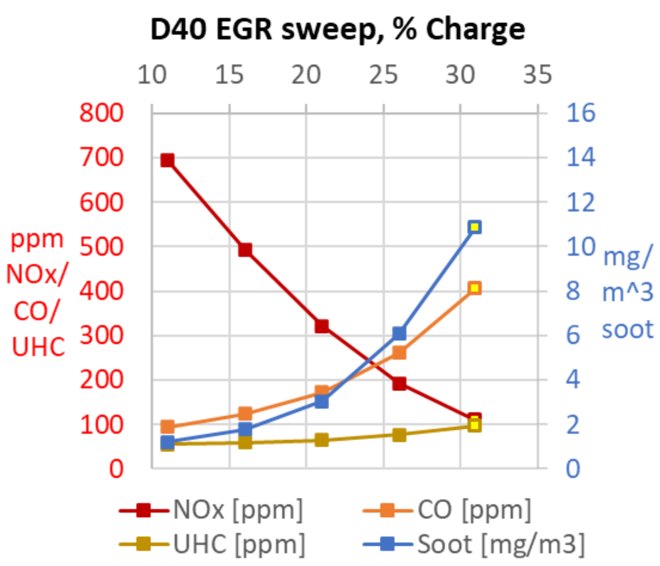
[1]Fioroni et al., SAE 2019-01-0570

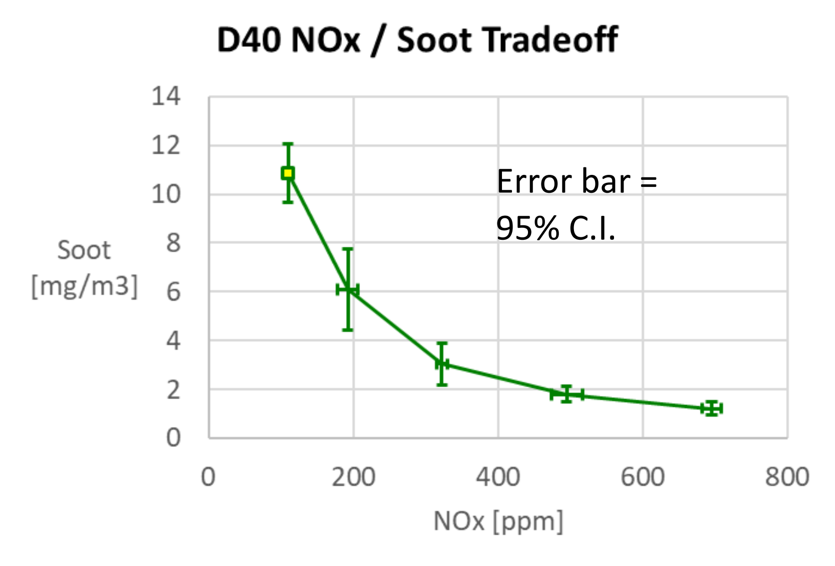
Mixing Controlled Compression Ignition Fuel Property Effects (Burton)

- **Cert ULSD baseline has been completed**
- **Results shown for D40 condition**
  - Top: SOI sweep
  - Bottom: EGR sweep
  - Expected MCCI emissions trends observed in both
- **Similar trends observed at A20 and G60 conditions**
  - A20: ~2x NOx, similar soot
  - G60: ~2x NOx, ~1.5x soot
- **Full MCCI performance range captured; will see how fuel properties from biofuel blends alter emissions & efficiency tradeoffs**









Approach
Fuel Effects on Oxidation Catalyst Performance

E.2.1.8: new FY 2020
E.2.2.8: ended FY 2019
E.2.2.9: continuing

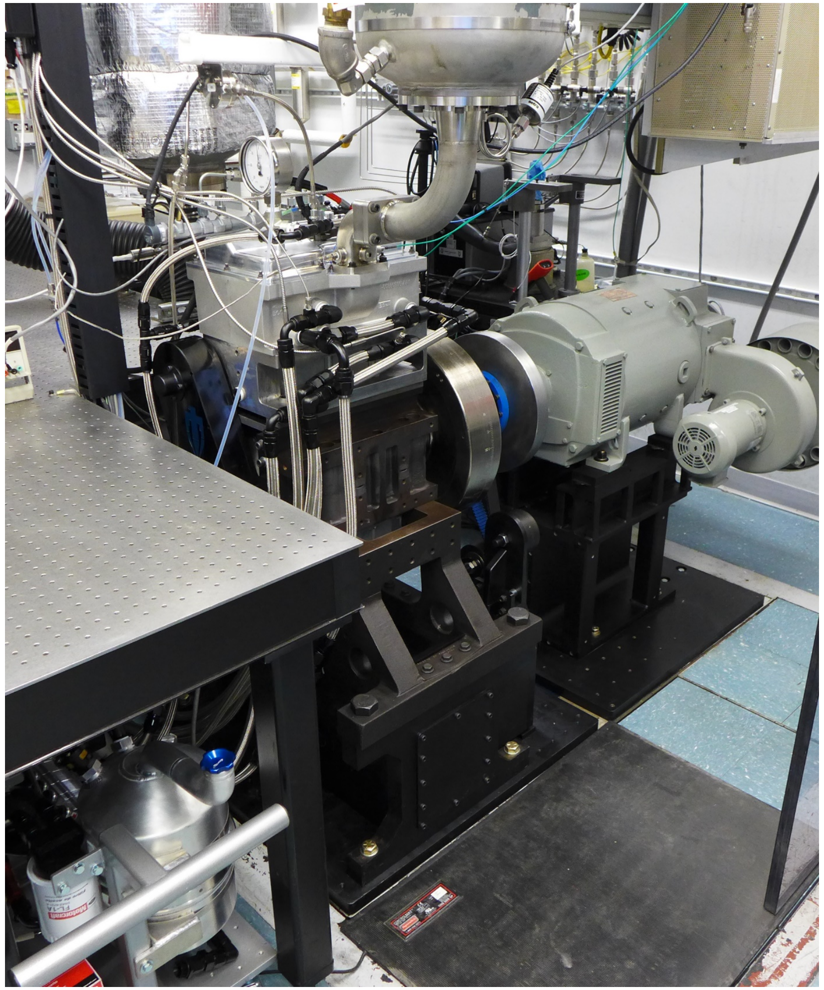
- **Cold start: MCCI cold-start strategies use retarded post injection to increase exhaust temperature and quickly reach catalyst light-off – limited by NOx/HC emissions[1].**
  - E.2.2.9 (Oxygenate approach, SNL): thermal, emissions, and optical measurements in a single-cylinder swirl-supported diesel engine using three different oxygenate blends with certification diesel
    - Are oxygenated blendstocks able to decrease pollutant emissions for a given exhaust temperature or enable later post injection combustion phasing?
    - Isolate cetane effects from oxygenate effects by blending with cetane improver: how do oxygenates affect ignition of late post injections?
    - Utilize 3D-RANS CFD simulations with a newly developed vapor-liquid equilibrium solver to provide insight into the reasons for the observed insensitivity of late post-injection heat-release to fuel cetane number
  - E.2.2.8 (Cetane approach, ORNL): Explore limits of post-injection strategy with high-CN renewable diesel on a multi-cylinder, heavy-duty diesel engine platform – directly applicable to new CARB emissions regulations (0.02 g/bhp-hr NOx)
    - Do the benefits of increasing CN continue proportionally or reach point of diminishing return?
    - Can further increases in exhaust temperature be made without increasing NOx/HC emissions?
    - Does high-CN fuel with late post create any unburned or partially-oxidized species that affect catalyst performance?
- **Low load: MCCI engines face challenge to meet new NOx regs where exhaust temperature too low for SCR operation – potential for multi-mode strategy in which ACI provides ultra-low engine-out NOx at low loads**
  - E.2.1.8 (ORNL): Quantify the effects of fuel properties on DOC light-off/light-down during mode switching between ACI and MCCI in a single-cylinder, MD diesel engine via total HC conversion (FID) and gaseous speciation (FTIR) before and after the DOC
    - How will lower exhaust temperature and higher engine-out HC/CO under ACI operation affect DOC light-off/light-down?
    - How will fuel properties such as cetane number and boiling range, and fuel components such as oxygenates and aromatics may impact the reactivity and storage of unburned and partially-oxidized HC to either promote or inhibit DOC activity during mode switching?

[1]Kurtz, E. and Polonowski, C., "The Influence of Fuel Cetane Number on Catalyst Light-Off Operation in a Modern Diesel Engine," SAE Int. J. Fuels Lubr. 10(3):2017, https://doi.org/10.4271/2017-01-9378.

Technical Accomplishments and Progress
Impact of oxygenates on catalyst heating operation (Busch)

E.2.2.9: continuing

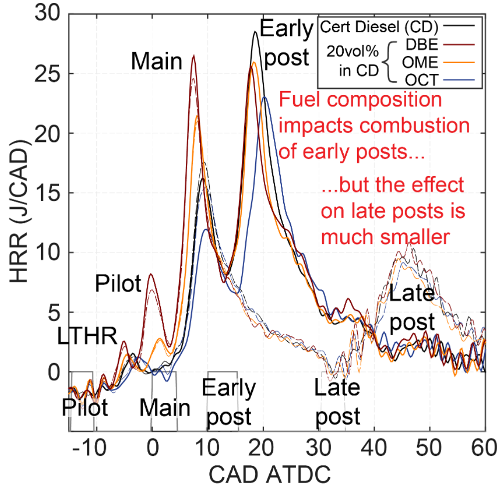
- **Sandia's new medium-duty diesel research engine has been commissioned and shakedown testing is ongoing**
  - Ford provided significant hardware, engineering, and technical assistance
- **Advantages over previous, light-duty optical diesel engine**
  - State-of-the-art combustion system (based on Ford 6.7L Power Stroke®)
  - Continuously fired operation (non-optical configuration)
    - Ability to quantify exhaust temperature/enthalpy
  - Online fuel flow measurement compliments offline hydraulic injection rate and quantity meter
- **Preparations are underway for the oxy fuel blends and cat heating study (Q3)**



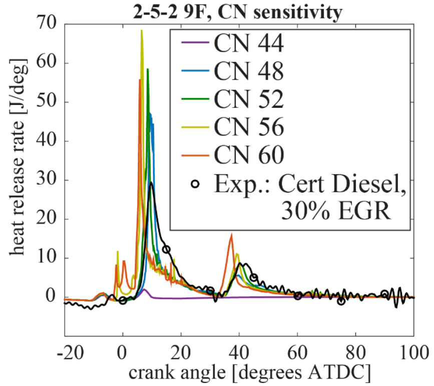
Technical Accomplishments and Progress
Impact of oxygenates on catalyst heating operation (Busch)

- **A novel spray modeling approach has been implemented to facilitate CFD simulation of injection and combustion into a wider range of in-cylinder conditions**
  - Vapor-liquid equilibrium solver by WERC: Federico Perini
- **Initial simulation results predict sensitivity of post heat-release to cetane number**
  - This conflicts with previous experimental findings, but supports findings in the literature that higher CN enables later post injections and higher exhaust temperatures[1]
- **Measurements on the new-medium duty diesel engine will distinguish cetane number effects from oxygenate effects (Q3)**

FY19 result: oxygenates do not affect late post heat-release, regardless of changes to CN



FY20 result: simulations do predict sensitivity of post heat-release to CN

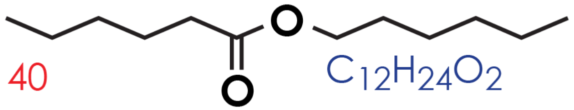


Pilot, main, and late post heat-release are all sensitive to cetane number

Cetane number of neat compound

Cert diesel: 43.9

Hexyl Hexanoate (HH)



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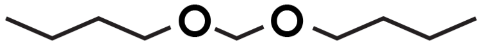
$C_{12}H_{24}O_2$

Dibutoxymethane(DBM)



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$C_9H_{20}O_2$

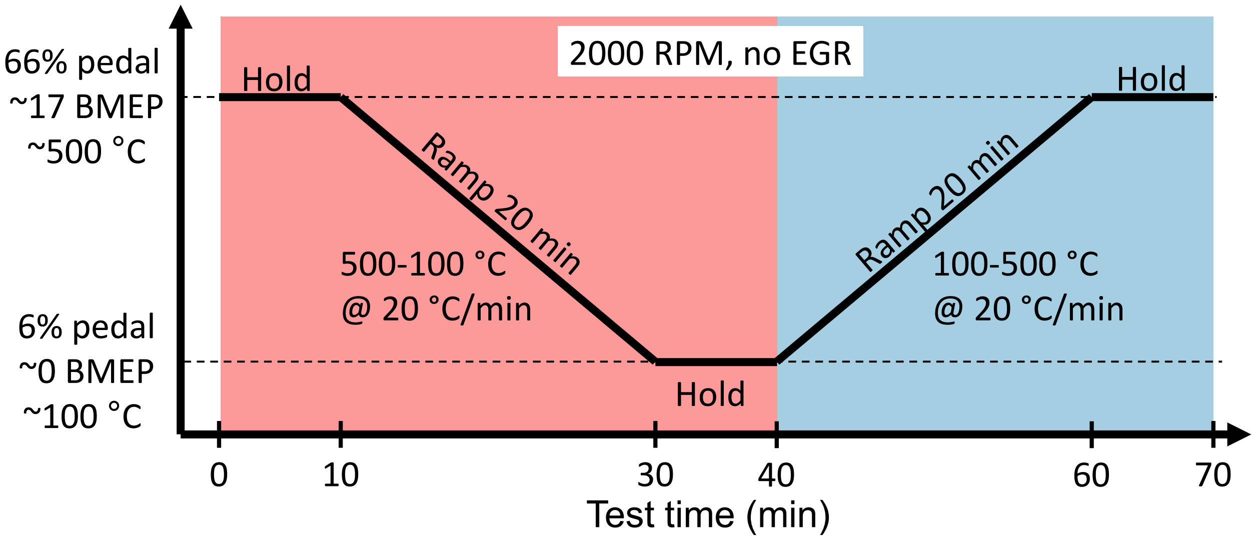
[1] Kurtz, E. and Polonowski, C., "The Influence of Fuel Cetane Number on Catalyst Light-Off Operation in a Modern Diesel Engine," SAE Int. J. Fuels Lubr. 10(3):2017, https://doi.org/10.4271/2017-01-9378.

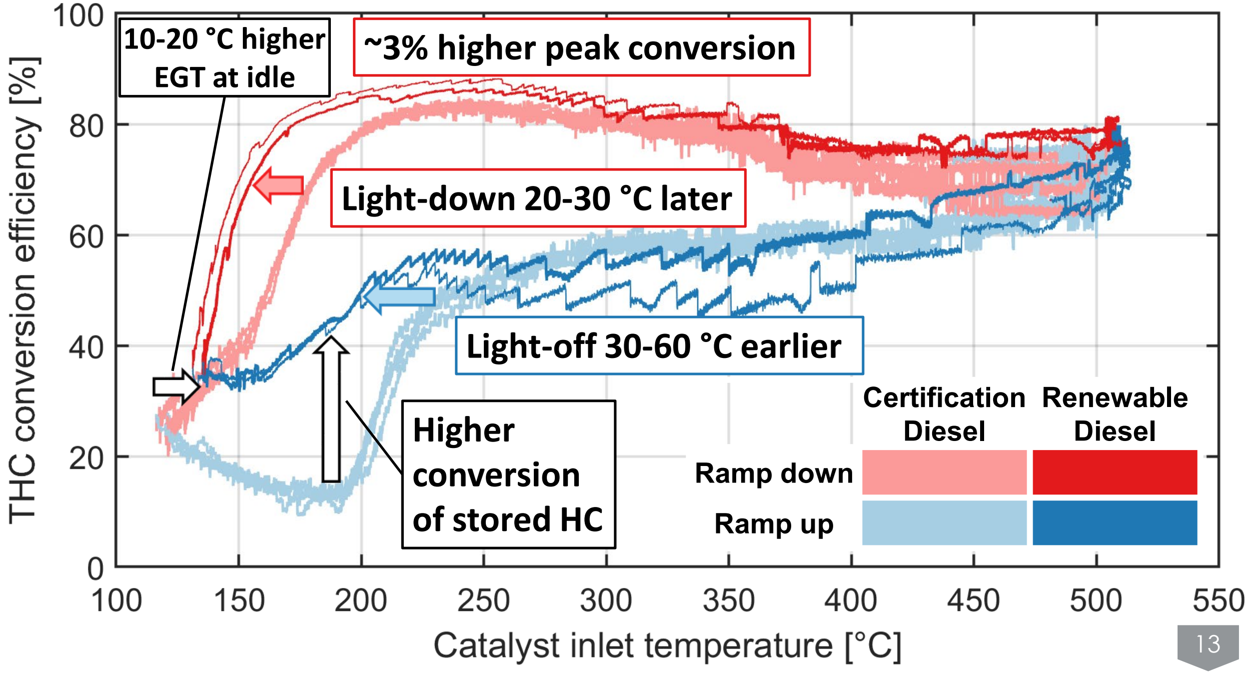
Technical Accomplishments and Progress
Impact of CN on catalyst light-off and cold-start emissions (Wissink)

E.2.2.8: ended FY 2019

- **Original plans to perform FY19 cold start experiments on DD15 multi-cylinder were cancelled due to hardware failure; transitioned to DOC light-off study on GM 1.9L multi-cylinder diesel engine (completed early FY20)**
- **Created load ramp cycle that emulates ACEC Low-Temperature Oxidation Catalyst Test Protocol temperature ramp (faster ramp rates, changing composition and space velocity)**
- **Aged model diesel oxidation catalyst[1]**
  - 300 cells/in^2 cordierite coated with 100 g/ft^3 Pt on 160 m^2/g γ-Al_2O_3
  - Instrumented with thermocouples at inlet/outlet and four axial locations inside catalyst
  - Simultaneous FID and FTIR measurements before and after catalyst
- **Paraffinic renewable diesel with high CN, tighter boiling range, and no aromatic content reduces light-off/light-down temperature and hysteresis, improves conversion of stored HC**

Fuel	CN	Boiling range (°C)			Aromatic (mass %)	LHV (kJ/g)
		T10	T50	T90		
2007 Cert. Diesel	45.6	208	258	309	29.5	42.6
Neste Ren. Diesel	74.8	260	281	293	0	~44



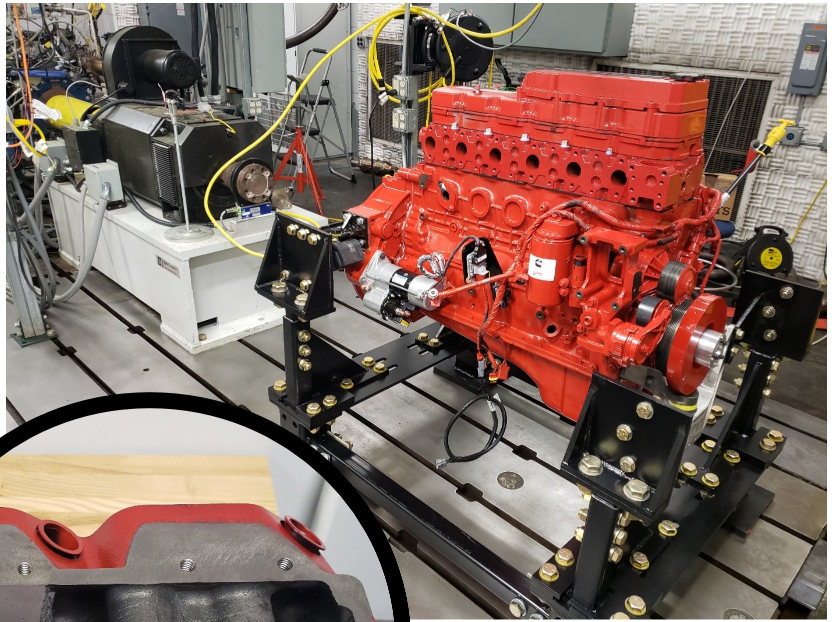


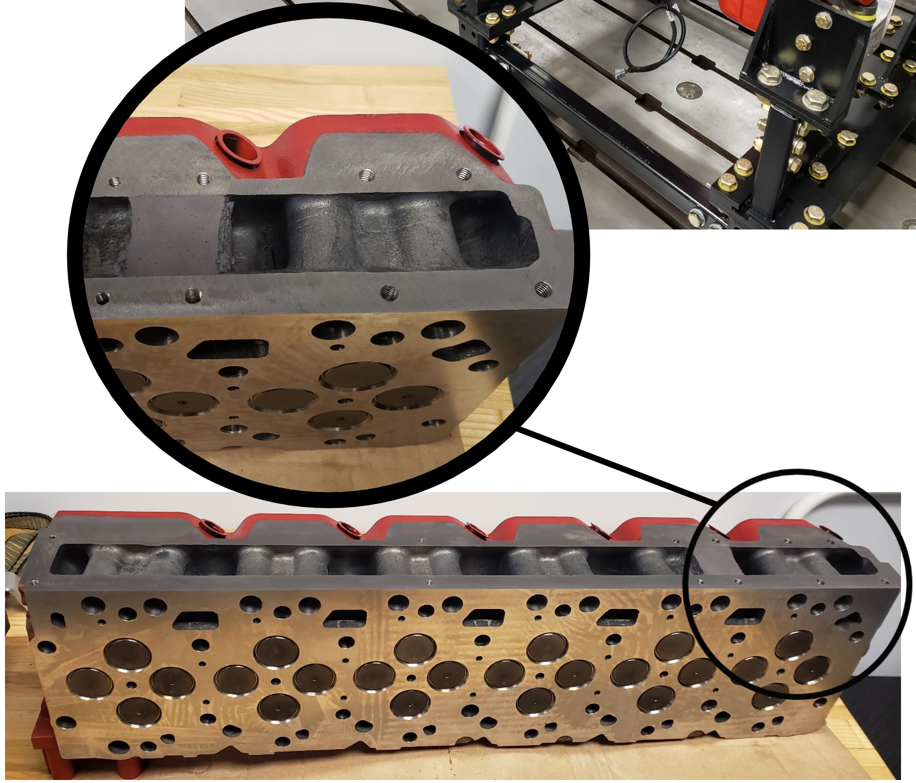
[1]Prikhodko et al, *SAE Int. J. Fuels Lubr.* 6(2):329-335, 2013

Technical Accomplishments and Progress
MD/HD Multimode Catalyst Light-off/Light-down (Wissink)

E.2.1.8: new FY 2020

- **Engine: 2019 Cummins 6.7L ISB modified to single-cylinder operation**
  - Bore x stroke: 107 mm × 124 mm, single cylinder displacement: 1.115 L
  - Leveraging resources/facilities with other ORNL tasks E.2.1.7 & E.2.2.7, which will share engine
- **Instrumented cylinder head provided by Cummins has been received**
- **Single-cylinder conversion and installation in progress**
  - Cylinder flow deactivation by machining cams
  - Cylinder compression deactivation by machining pistons
  - Modification of cast intake manifold to isolate flow to single cylinder
  - Modification of coolant and oil systems to allow for external control
- **Aftertreatment system from Ford 6.7L Power Stroke has been acquired**
  - Representative of modern MD segment (MY2019 Ford F250)
  - DOC will be aged and cored to 1/6 volume to achieve representative space velocity for single-cylinder operation
- **Currently on track to perform experiments in support of Sept 2020 milestone, but anticipate that work-from-home restrictions related to COVID-19 may impact build activity and supplier lead times**





Responses to Previous Year Reviewers' Comments

- **Simulations should be applied to catalyst heating operation**
  - Agreed. We've been developing simulation capabilities to simulate this complex mode of operation and will continue to utilize simulations to provide supplemental insight whenever possible.
- **Post-injection sooting impacts need further investigation**
  - Engine-out smoke emissions will be characterized during planned experiments with the new medium-duty diesel engine
- **Will other approaches to solving cold-start problems be considered downstream?**
  - Current engine hardware limitations preclude study of some of the more popular engineering approaches to address cold starting (e.g. cylinder deactivation and variable valve timing). The current approach within this Co-Optima project is to build fundamental understanding of fuel effects on this combustion regime.
- **Cavitation work seems especially disconnected from key Co-Optima objectives**
  - Cavitation work was not continued as part of Co-Optima in FY20, but it is continuing under the Advanced Combustion HD program (without the fuels aspect)
- **For the cavitation measurements and simulation, more extensive experimental measurements are required to validate the simulations, and longer tests for erosion need to be prioritized**
  - Research on cavitation and erosion has been moved to the core program studying heavy duty sprays and includes more extensive experiments and simulations.
- **For CN-focused cold start experiments, reviewers suggested using conventional diesel fuels with more moderate range of CN**
  - Results from that approach have already been reported in the literature and do not address the potential of alternative fuels with high CN to improve cold-start strategy. However, distillate fuels with more moderate CN range are being proposed for FY21 multimode task.

Any proposed future work is subject to change based on funding levels

Collaboration and Coordination with Other Institutions

In-Cylinder Emissions Reduction	E.1.4.1 Powell Argonne	**X-ray Measurements of Injection and Mixture Formation** • Argonne: Simulations team and Advanced Photon Source • Sandia, Engine Combustion Network: Injectors for study, choice of operating conditions, dissemination of result
	G.2.18 Som Argonne	**Effect of Fuel Properties on In-nozzle Cavitation and Ensuing Spray Using CFD** • Argonne: X-ray Team (C. Powell) • Sandia, ECN: Injectors for study, choice of operating conditions, dissemination of results • University of Perugia, Italy (M. Battistoni)
	F.2.4.1 Burton NREL	**Mixing Controlled Compression Ignition Fuel Property Effects** • Ford Motor Company – Engine support, technical collaboration
In-Cylinder Effects on Emissions Control	E.2.2.9 Busch SNL	**Impact of oxygenates on catalyst heating operation** • Subcontractor: Wisconsin Engine Research Consultants (W-ERC) - CFD simulations, model development • Industry: Ford Motor Company - Technical discussions, engineering support
	E.2.2.8 Wissink ORNL	**Impact of cetane number and volatility on catalyst light-off and cold-start emissions** • Daimler, Ford: Technical discussions and support • Neste: Renewable diesel
	E.2.1.8 Wissink ORNL	**MD/HD Multimode Catalyst Light-off/Light-down** • Cummins: Instrumented cylinder head, technical discussions and support

Remaining Challenges and Barriers

In-Cylinder Emissions Reduction	E.1.4.1 Powell Argonne	**X-ray Measurements of Injection and Mixture Formation** • Only a limited range of fuels have been tested, all alkanes. This has limited the range of fuel properties that could be explored
	G.2.18 Som Argonne	**Effect of Fuel Properties on In-nozzle Cavitation and Ensuing Spray Using CFD** • Effect of internal nozzle flow on ensuing spray was validated for one fuel only (n-dodecane). Evaluation of fuel properties on the spray effect would require experimental near-nozzle X-ray data that are not currently available.
	F.2.4.1 Burton NREL	**Mixing Controlled Compression Ignition Fuel Property Effects** • Fully understanding biomass derived fuel effects on combustion, emissions and performance
In-Cylinder Effects on Emissions Control	E.2.2.9 Busch SNL	**Impact of oxygenates on catalyst heating operation** • Lack of understanding of how oxygenates affect pollutant formation mechanisms
	E.2.2.8 Wissink ORNL	**Impact of cetane number and volatility on catalyst light-off and cold-start emissions** • Cold-start study was not able to be completed in 1-year task timeline due to engine failure. Point of diminishing return for increased CN and effects of unburned or partially-oxidized species on catalyst performance not yet understood.
	E.2.1.8 Wissink ORNL	**MD/HD Multimode Catalyst Light-off/Light-down** • FY20 effort focused on CN and aromatic content. Other fuel properties such as boiling range and oxygenate content are likely to have significant impact and remain to be studied.

Proposed Future Research

In-Cylinder Emissions Reduction	E.1.4.1 Powell Argonne	**X-ray Measurements of Injection and Mixture Formation (ended FY19)** • Expand the range of fuel studied to include aromatics, bio-blends
	G.2.18 Som Argonne	**Effect of Fuel Properties on In-nozzle Cavitation and Ensuing Spray Using CFD (ended FY19)** • Continue coordinated effort with X-ray team to validate approaches that couple internal nozzle flow and ensuing spray. Evaluate effect of said approaches on mixing, emissions and engine performance.
	F.2.4.1 Burton NREL	**Mixing Controlled Compression Ignition Fuel Property Effects (ending FY20)** • Investigation of impacts on emissions with various biomass blends level
In-Cylinder Effects on Emissions Control	E.2.2.9 Busch SNL	**Impact of oxygenates on catalyst heating operation** • FY21: Development and application of time-resolved measurement of UHC/CH2O/soot in exhaust
	E.2.2.8 Wissink ORNL	**Impact of cetane number and volatility on catalyst light-off and cold-start emissions (ended FY19)** • Fuel property effects on catalyst performance under cold-start operation on dedicated research platform
	E.2.1.8 Wissink ORNL	**MD/HD Multimode Catalyst Light-off/Light-down** • Quantify effects of fuel boiling range on DOC light-off/light-down using distillates (#2 ULSD, #1 ULSD, “#0” ULSD)

Any proposed future work is subject to change based on funding levels

Summary

In-Cylinder Emissions Reduction	E.1.4.1 Powell Argonne	**X-ray Measurements of Injection and Mixture Formation (ended FY19)** • Measurements have found variations in cavitation with fuel properties. • The results have been used to validate the efforts of the simulations team
	G.2.18 Som Argonne	**Effect of Fuel Properties on In-nozzle Cavitation and Ensuing Spray Using CFD (ended FY19)** • Time-resolved X-ray measurements revealed the flow separation inside the nozzle • Simulations correctly captured the 3-D distribution of the low-density fluid observed in experiments • CFD provided insights in the composition of the gas phase highlighting the effects of fuel properties
	F.2.4.1 Burton NREL	**Mixing Controlled Compression Ignition Fuel Property Effects (ending FY20)** • Investigation of impacts on emissions with various biomass blends level
In-Cylinder Effects on Emissions Control	E.2.2.9 Busch SNL	**Impact of oxygenates on catalyst heating operation** • Ongoing work with the new medium-duty diesel research engine should clarify the effects of oxygen content and cetane number
	E.2.2.8 Wissink ORNL	**Impact of cetane number and volatility on catalyst light-off and cold-start emissions (ended FY19)** • DOC light-off study during controlled temperature ramp showed that paraffinic renewable diesel with high CN, tighter boiling range, and no aromatic content reduces light-off/light-down temperature and hysteresis, improves conversion of stored HC compared to certification diesel
	E.2.1.8 Wissink ORNL	**MD/HD Multimode Catalyst Light-off/Light-down** • New single-cylinder engine platform will allow for understanding of fuel effects on DOC performance under MD/HD multimode operating conditions using real engine exhaust.

Reviewer-Only Slides

Publications and Presentations

Publications

- "Time-resolved 3D imaging of two-phase fluid flow inside a steel fuel injector using synchrotron X-ray tomography", Aniket Tekawade, Brandon A. Sforzo, Katarzyna E. Matusik, Kamel Fezzaa, Alan L. Kastengren, Christopher F. Powell. Scientific Reports, Accepted for Publication, February 2020.
- "Internal Nozzle Flow Simulations of the ECN Spray C Injector under Realistic Operating Conditions", H. Guo, R. Torelli, A. B. Rodriguez, A. Tekawade, B. Sforzo, C. F. Powell, S Som, SAE World Congress, 2020
- Guo, H., Torelli, R., Som, S. et al., "CFD Modeling of Fuel Injection via Coupling of Internal Nozzle Flow and Ensuing spray," ILASS Americas 2020, submitted.
- Guo, H., Torelli, R., Bautista Rodriguez, A., Tekawade, A. et al., "Internal Nozzle Flow Simulations of the ECN Spray C Injector under Realistic Operating Conditions," SAE Technical Paper 2020-01-1154, 2020 (accepted).

Presentations

- Guo, H., Torelli, R., Som, S., "CFD Modeling of Fuel Injection via Eulerian-Lagrangian One-Way Coupling of Nozzle Flow and the Ensuing spray," AEC Program Review Meeting, Livermore, CA, USA, February 5, 2020.
- Guo, H., Torelli, R., Som, S., "In-nozzle flow Large Eddy Simulations of ECN Spray C under Realistic Operating Conditions with N-dodecane and Iso-octane Fuels," ECN 6.9 Web Meeting, September 5, 2019.
- Torelli, R., Guo, H., Som, S., "High-fidelity Modeling of Fuel Injection and Application of Best Practices to Practical Injectors," AEC Program Review Meeting, Southfield, MI, USA, August 15, 2019.
- "High-Speed Imaging of Catalyst Heating Operating Strategies in an Optical Diesel Engine", Presented at AEC Program Review Meeting, USCAR, Southfield, MI, August 14, 2019.
- "3D Imaging of Cavitating Flow in a Diesel Injector at Practical Conditions using X-ray micro-CT", A. Tekawade, B. Sforzo, A. Kastengren, K. Matusik, C. F. Powell. 30th Annual Conference on Liquid Atomization and Spray Systems, Tempe, AZ, May 2019
- Aniket Tekawade, Brandon Sforzo, Alan Kastengren, Katarzyna Matusik, Christopher Powell, "Application of synchrotron x-ray imaging and micro-CT to 4D visualization of multiphase flow inside a steel fuel nozzle", SPIE Optics + Photonics, https://doi.org/10.1117/12.2527585, San Diego, CA, August 2019
- "3D Measurements of the Geometry, Internal Flow and Emerging Fuel Jet from the ECN Spray C Injector", Brandon Sforzo, Aniket Tekawade, Katarzyna E. Matusik, Alan L. Kastengren, Christopher F. Powell. 29th European Conference on Liquid Atomization and Spray Systems, 2-4 September 2019.

Critical Assumptions and Issues

In-Cylinder Emissions Reduction	E.1.4.1 Powell Argonne	**X-ray Measurements of Injection and Mixture Formation (ended FY19)** • Cavitation vapor, air dissolved in the fuel, and ambient gas entering the nozzle through hydraulic flip are impossible to distinguish from one another in the current measurements. Future measurements can be designed to resolve these effects.
	G.2.18 Som Argonne	**Effect of Fuel Properties on In-nozzle Cavitation and Ensuing Spray Using CFD (ended FY19)** • None reported
	F.2.4.1 Burton NREL	**Mixing Controlled Compression Ignition Fuel Property Effects (ending FY20)** • None reported
In-Cylinder Effects on Emissions Control	E.2.2.9 Busch SNL	**Impact of oxygenates on catalyst heating operation** • Blends of up to 30% of bio-blendstocks will make a sufficient impact on vehicular CO2 emissions
	E.2.2.8 Wissink ORNL	**Impact of cetane number and volatility on catalyst light-off and cold-start emissions (ended FY19)** • Original planned experiments were cancelled due to engine hardware failure, with no replacement available. Any future efforts on cold-start should use a dedicated research platform with contingency for hardware failures.
	E.2.1.8 Wissink ORNL	**MD/HD Multimode Catalyst Light-off/Light-down** • New single-cylinder Cummins ISB platform will be commissioned and operational in time to support experimental efforts for Co-Optima tasks E.2.1.7, E.2.1.8, E.2.2.7